New measurements of magnetic fields of roAp stars with FORS 1 at the VLT [*]

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Abstract. Magnetic fields play a key role in the pulsations of rapidly oscillating Ap (roAp) stars since they are a necessary ingredient of all pulsation excitation mechanisms proposed so far. This implies that the proper understanding of the seismological behaviour of the roAp stars requires knowledge of their magnetic fields. However, the magnetic fields of the roAp stars are not well studied. Here we present new results of measurements of the mean longitudinal field of 14 roAp stars obtained from low resolution spectropolarimetry with FORS1 at the VLT.

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1. Introduction

Helioseismology has proved a powerful tool to investigate important basic properties of the solar interior (Gough 2000). Likewise, asteroseismology has the potential to provide new insights into the physics of stellar interiors. Among the most promising objects that can be studied through this technique are the roAp stars. These are cool chemically peculiar stars which pulsate in high-overtone ($n \gg l$), low-degree ($l \leq 3$) p-modes with periods from about 6 to 15 min and typical photometric B amplitudes of a few mmag. There are 32 such stars currently known. Detailed reviews of the roAp stars have been published by Kurtz (1990), Matthews (1991), Martinez & Kurtz (1995) and Kurtz (2003).

The pulsations of the roAp stars are strongly affected by their magnetic fields (Bigot et al. 2000; Cunha & Gough 2000). Of particular importance is the recent work by Bigot & Dziembowski (2002). Their theory of the interaction of rotation, pulsation and the magnetic field suggests a new model, the improved oblique pulsator model, that is a significant departure from the standard oblique pulsator model for roAp stars. They suggest that the light variations are caused by a pulsation mode in which the stellar surface moves in a plane that is inclined to both the rotation and the magnetic axes of the star. The displacement vector describes an ellipse in that plane with the pulsation period, and the whole pattern rotates with the rotation of the oblique magnetic field.

Obviously, magnetic fields play a key role in the pulsations, which can only be properly interpreted if the strength and structure of these fields are known. Despite of the importance of magnetic fields for the proper understanding of pulsational properties of roAp stars, these fields have scarcely been studied until now. Among 32 roAp stars 20 definitely or very probably have a magnetic field (Mathys 2003), but of these 20, only three stars, HD 12098, HD 24712 and HD 83368, have been studied throughout their rotation periods (Lüftinger et al. 2003; Mathys & Hubrig 1997). Here we present new results of measurements of the mean longitudinal field of 14 roAp stars obtained from low resolution spectropolarimetry with FORS1 at the VLT.

2. Observations and data reduction

The observations reported here have been carried out between July and September 2002 at the European Southern Observatory with FORS 1 (FOcal Reducer low dispersion Spectrograph) mounted on the 8-m Melipal telescope of the VLT. This multi-mode instrument is equipped with polarization analyzing optics comprising super-achromatic half-wave and quarter-wave phase retarder plates, and a Wollaston prism with a beam divergence of $22''$ in standard resolution mode. For 13 stars we used the GRISM 600B in the wavelength range 3480–5890 Å to cover all hydrogen Balmer lines from Hβ to the Balmer jump (Appenzeller et al. 1998). One star, HD 6532, has been observed with GRISM 600R in the region which includes Hα and Hβ, from 4770 to 6900 Å. Both grisms have 600 grooves mm^{-1}; with the narrowest available slit width

Table 1. Wavelength ranges around the hydrogen Balmer lines.

Line(s)	Wavelength range [Å]
H_{16}-H_{10}	$3701 - 3801$
H_9	$3820.5 - 3852.5$
H_8	$3870.2 - 3910.2$
$H\epsilon$	$3941.2 - 4001.2$
$H\delta$	$4082.9 - 4122.9$
$H\gamma$	$4311.7 - 4371.7$
$H\beta$	$4812.7 - 4912.7$
$H\alpha$	$6512 - 6612$

of $0\rlap{.}{''}4$ they give a spectral resolving power of R∼2000 and R∼2900, respectively.

Wavelength calibrations were taken during day time for the two different retarder waveplate setups (α=+45° and −45°) that were used for the observations. Wavelength calibration was performed by associating with each individual science spectrum the calibration frame obtained with the similar orientation of the retarder waveplate. Ordinary and extraordinary beams were independently calibrated with the corresponding beams of the reference spectrum. As has been previously shown by Landstreet (1982), in the weak field regime, the mean longitudinal field can be derived from the difference between the circular polarizations observed in the red and blue wings of the hydrogen line profiles using the formula

$$\frac{V}{I} = -\frac{g_{\text{eff}} e \lambda^2}{4\pi m_e c^2} \frac{1}{I} \frac{\mathrm{d}I}{\mathrm{d}\lambda} \langle \mathcal{B}_z \rangle, \tag{1}$$

where V is the Stokes parameter which measures the circular polarization, I is the intensity in the unpolarized spectrum, g_{eff} is the effective Landé factor, e is the electron charge, λ is the wavelength, m_e the electron mass, c the speed of light, $\mathrm{d}I/\mathrm{d}\lambda$ is the derivative of Stokes I, and $\langle \mathcal{B}_z \rangle$ is the mean longitudinal field. To minimize the crosstalk effect we executed the sequence $+45 - 45$, $+45 - 45$, $+45 - 45$ etc. and calculated the values V/I using:

$$\frac{V}{I} = \frac{1}{2} \left\{ \left(\frac{f^{\text{o}} - f^{\text{e}}}{f^{\text{o}} + f^{\text{e}}}\right)_{\alpha=-45°} - \left(\frac{f^{\text{o}} - f^{\text{e}}}{f^{\text{o}} + f^{\text{e}}}\right)_{\alpha=+45°} \right\}, \tag{2}$$

where α gives the position angle of the retarder waveplate and f^{o} and f^{e} are ordinary and extraordinary beams, respectively. Stokes I values have been obtained from the sum of the ordinary and extraordinary beams. In our calculations we assumed a Landé factor g_{eff}=1 for hydrogen lines. More details of the observing technique are given by Bagnulo et al. (2002) and Hubrig et al. (2003).

The errors of the measurements of the polarization have been determined from photon counting statistics and have been converted to errors of field measurements. For each roAp star we usually took 4 to 13 continuous series of 2 exposures with the retarder waveplate oriented at different angles. The spectropolarimetric capability of the FORS 1 instrument in combination with the large light collecting power of the VLT allowed us to achieve a S/N

ratio up to 2000 per pixel in the one–dimensional spectrum, as required to detect low polarization signatures produced in the spectral lines by longitudinal magnetic fields of the order of a few hundred Gauss.

3. Results

The basic data of our sample of roAp stars are presented in Table 2. The columns are, in order, the HD number of the star, another identifier, the visual magnitude, the spectral type as it appears in the catalogue of Renson et al. (1991), the pulsation period, the heliocentric Julian date of mid–observation, number of series N and the longitudinal magnetic field $\langle \mathcal{B}_z \rangle$ and its estimated uncertainty σ_z. The star HD 9563 shows the highest uncertainty of the magnetic field measurements ($\sigma_z = 325\,\text{G}$) because the exposure was taken in deteriorating weather conditions. Among the roAp stars studied, the rotation period is known only for the star HD 6532 ($\text{P}_{\text{rot}} = 1\overset{d}{.}94497$; Kurtz et al. 1996).

In the following we give a brief overview of the previous knowledge of magnetic fields in the studied roAp stars. The most recent compilation of the measurements of magnetic fields in roAp stars is given by Mathys (2003). Although the presence of a magnetic field is required by all the pulsation-driving mechanisms that have been proposed, knowledge of the magnetic fields of roAp stars is still very incomplete. Apart from HD 6532, all stars in our sample are poorly studied. For six of the stars presented here the spectropolarimetric magnetic field measurements are the first to have been made. We note here that the previous magnetic field data mentioned below are presented in greater detail in Mathys & Hubrig (1997) and Mathys & Hubrig (2003, in preparation).

3.1. Notes on individual stars

HD 6532: The 6.9-min pulsations in this star were discovered by Kurtz & Kreidl (1985). This star is singly periodic with a rotationally modulated frequency quintuplet (Kurtz et al. 1996). It is also the only star in our sample for which a short rotation period ($\text{P}_{\text{rot}} = 1\overset{d}{.}94497$) has been determined (see Kurtz et al. 1996 and references therein). The spectral lines show significant Doppler broadening which complicates the magnetic field determination using high–resolution spectropolarimetry (Mathys & Hubrig 1997). An estimate of $v \sin i < 47$ km s^{-1} has been determined from CASPEC spectra obtained with the ESO 3.6 m spectrograph (Mathys & Hubrig 2003, in preparation). The major advantage of using low-resolution spectropolarimetry with FORS 1 is that polarization can be detected in relatively fast rotators as we measure the field in the hydrogen Balmer lines. Our determination of the longitudinal field yields a null value for this star.

HD 9289: The 10.5-min pulsations in this star were discovered by (Kurtz 1993). A later study (Kurtz et al. 1994) found the star to be multi-periodic with alternating even and odd ℓ-modes, similar to the well-studied roAp star

Table 2. Basic data of studied roAp stars and their magnetic fields measured with the FORS 1 instrument on the VLT UT3 (Melipal).

HD	Other identifier	V	Sp. Type	P_{puls} [min]	HJD 2452000+	N	$\langle \mathcal{B}_z \rangle$ [G]
6532	CD -27°355	8.4	A3 Sr Cr	6.9	531.915	13	215 ± 158
9289	BD -11°286	9.4	A3 Sr Eu	10.5	519.751	4	654 ± 130
12932	BD -19°384	10.4	A5 Sr Eu	11.6	517.884	5	638 ± 169
99563	BD -08°3173	8.2	F0 Sr	11.2	494.483	5	-688 ± 325
122970	BD +06°2827	8.3	F0	11.1	494.500	5	216 ± 125
161459	CD -51°11145	10.4	A2 Eu Sr Cr	12.0	476.622	4	-1755 ± 224
185256	CD -30°17252	9.9	F0 Sr Eu	10.2	476.676	4	-706 ± 180
190290	CPD -79°1062	9.9	A0 Eu Sr	7.3	494.561	5	3220 ± 164
190290	CPD -79°1062	9.9	A0 Eu Sr	7.3	498.529	5	3250 ± 248
193756	CPD -52°11681	9.2	A9 Sr Cr Eu	13.0	498.575	10	-193 ± 136
196470	BD -18°5731	9.8	A2 Sr Eu	10.8	476.732	4	1474 ± 202
203932	CD -30°18600	8.8	A5 Sr Eu	5.9	498.615	4	-267 ± 143
213637	BD -20°6447	9.6	F1 Eu Sr Cr	11.5	498.653	8	740 ± 141
217522	CD -45°14901	7.5	A5 Sr Eu Cr	13.7	498.687	4	-725 ± 176
218495	CPD -64°4322	9.3	A2 Eu Sr	7.4	519.725	4	-912 ± 142

HR 1217 (Kurtz et al. 2002). This star was observed only once with CASPEC (Mathys & Hubrig 2003, in preparation), giving a nonzero longitudinal field of about 400 G. A longitudinal magnetic field of (654 ± 130) G has been diagnosed from the FORS 1 spectra.

HD 12932: The 11.6-min pulsations in this star were discovered by Schneider & Weiss (1990). This star is poorly studied, but appears to be singly periodic. A previous measurement with CASPEC (Mathys & Hubrig 2003, in preparation) revealed a longitudinal field of 400 G. From the FORS 1 spectra we derive $\langle \mathcal{B}_z \rangle = (638 \pm 169)$ G.

HD 99563: The 11.2-min pulsations in this star were discovered by Dorokhova & Dorokhov (1998). The longitudinal magnetic field in this star at 2.1σ level is reported here for the first time.

HD 122970: The 11.1-min pulsations in this star were discovered by Handler & Paunzen (1999) and studied in greater detail in two multi-site campaigns by Handler et al. (2002) who found two modes of different degree, ℓ, in both data sets, along with frequency and amplitude modulation. A marginal hint of a longitudinal magnetic field in this star is reported here for the first time. Ryabchikova et al. (2000) determined a surface magnetic field of 2.3 kG from the modelling of the rear–earth line profiles.

HD 161459: The 12.0-min pulsations in this star were discovered by Martinez & Kauffmann (1991) and studied further by Martinez et al. (1991). The presence of a magnetic field in this star is reported here for the first time.

HD 185256: The 10.2-min pulsations in this star were discovered by Kurtz & Martinez (1995). The presence of a magnetic field in this star is reported here for the first time.

HD 190290: The multi-periodic 7.3-min pulsations in this star were discovered by Martinez & Kurtz (1990a) and studied further by Martinez et al. (1991). The presence of a magnetic field in this star is established here for the first time, via two measurements. This star shows the strongest

longitudinal magnetic field (in absolute value) measured so far in any of the 32 known roAp stars. The two magnetic field measurements were separated by 4 days, but no significant variation was found between them.

HD 193756: The 13.0-min pulsations in this star were discovered by Martinez & Kurtz (1990b). An attempt to detect the magnetic field in this star was made by Mathys & Hubrig (1997), but no field was detected. We are not able to detect a longitudinal magnetic field on the FORS 1 spectra.

HD 196470: The 10.8-min pulsations in this star were discovered by Martinez et al. (1990). The presence of a magnetic field in this star is reported here for the first time.

HD 203932: The 5.9-min pulsations in this star were discovered by Kurtz (1984). This is one of the shortest periods known for the roAp stars; only HD 134214 has a shorter period at 5.7 min. Further study by Martinez et al. (1990) indicated the presence of some transient frequencies. Two previous attempts to measure the magnetic field in this star (Mathys & Hubrig 1997) yielded no detection. A longitudinal field of about -150 G was detected from a CASPEC spectrum by Mathys & Hubrig (2003, in preparation). As the accuracy of our determination on FORS 1 spectra is significantly worse than the accuracy achieved with CASPEC spectra for this star (≈ 40 Gauss), the longitudinal field could not be diagnosed.

HD 213637: The 11.5-min pulsations in this star were discovered by Martinez et al. (1998). Resolved magnetically split lines have been observed in this star by Mathys (2003) and Kochukhov (2003).

HD 217522: The 13.7-min pulsations in this star were discovered by Kurtz (1983). Further observations by Kreidl et al. (1991) found another pulsation mode with a period of 8.3 min that was not present in the discovery data set, indicating transient modes, or strong amplitude modulation. The first magnetic observation of this star

did not show any significant longitudinal magnetic field (Mathys & Hubrig 1997). Here we report the detection of a longitudinal field from the FORS 1 spectra at the 4.1σ level.

HD 218495: The 7.4-min pulsations in this star were discovered by Martinez & Kurtz (1990b). Both previous determinations of the longitudinal field by Mathys & Hubrig (1997) yielded nonzero values at a low level of significance. A longitudinal field at the 6.4σ level has been diagnosed from the FORS 1 spectra.

4. Discussion

The presence of non-zero mean longitudinal fields in 11 roAp stars gives an indication that magnetic fields of a few hundred gauss up to a few kilogauss are widespread among roAp stars. There are only three stars, HD 6532, HD 99563 and HD 193756, for which a magnetic field has not been detected at a level of 3σ or higher in the present and preceding studies. Our results seem to hint that stronger magnetic fields tend to be found in hotter stars. Indeed, the stars of spectral type A0 and A2, HD 190290, HD 161459, HD 196470 and HD 218495 show the largest longitudinal fields. Hubrig et al. (2000a) have already reported about the existence of such a trend in their study of the evolutionary state of magnetic Ap stars. We should note that for roAp stars the effective temperatures derived from photometry are not in good agreement with the spectral classification (e.g., Kurtz 2002; North 2003, private communication). Because of the extremely anomalous energy distribution of these stars, the calibration of the photometric temperature indicators are frequently questioned. The inconsistencies can only be resolved by adopting effective temperatures inferred from detailed spectroscopic studies. In addition, because of the strong dependence of the longitudinal field on the rotational aspect, its usefulness to characterise actual field strength distributions is limited, but this can be overcome, at least in part, by repeated observations to sample various rotation phases, hence various aspects of the field.

Two related outstanding problems in our understanding of the nature of the roAp stars are the pulsation driving mechanism and the mode selection mechanism (see Shibahashi (2003) for discussion and references). The magnetic roAp stars pulsate only in high overtone modes while the non-magnetic δ Sct stars pulsate mostly in low overtone modes. Since these stars overlap in the H-R diagram, it is strongly suspected that the magnetic field plays a major role, whether directly or indirectly, in the driving and mode selection mechanisms. Except for HD 122970 and HD 217522, the stars in our sample do not have accurately determined Hipparcos parallaxes, hence their positions in the H-R diagram cannot be reliably determined. Nevertheless, in our recent study (Hubrig et al. 2000b) we were able to show that the domains of the roAp stars and the non-oscillating Ap (noAp) stars largely overlap in the H-R diagram. As this means that mass and internal structure differences between the roAp and noAp stars

cannot be the only decisive factor in their respective evolution, the question arises whether another key factor plays a role in the excitation and mode selection mechanisms. The magnetic field is a likely candidate to be this factor. It is clearly necessary to understand the character of the surface magnetic fields in as much detail as possible.

These are the reasons why we are studying the magnetic field structure of the roAp stars. As mentioned by Mathys (2003) there is an unusually high frequency of occurrence of strong magnetic fields and of slow rotation among roAp stars. Seven roAp stars with magnetically resolved lines have already been detected since the discovery of pulsations more than 20 years ago. However, quite a number of roAp stars have rather weak or undetectable longitudinal fields and strong quadratic fields (Mathys & Hubrig 1997). The determination of the quadratic field is based on the differential broadening that the field induces in unpolarized spectral lines having different magnetic sensitivities (for more details on the derivation of the quadratic magnetic field, see Mathys 1999). The rotational phase coverage achieved by the existing magnetic field data is insufficient and the structure of the magnetic fields in these roAp stars is presently unknown. Yet, from our results, it must be sufficiently tangled that it does not produce strong observable polarization signature. Clearly, further systematic studies of magnetic fields in these stars should be conducted with a view to derive the geometrical structure of the fields. To understand better the origin of pulsations the derived models of magnetic fields must then to be confronted with the pulsation properties of the roAp stars.

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